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Khan, Mohammad Rezwan; Mulder, Grietus ; Van Mierlo, Joeri ; Kær, Søren Knudsen

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THE INTEGRATION AND CONTROL OF MULTIFUNCTIONAL STATIONARY PV-BATTERY SYSTEMS IN SMART DISTRIBUTION GRID

Mohammad Rezwan Khan[1,*], Grietus Mulder[2], Joeri Van Mierlo[3], Søren Knudsen Kær[1]
1. Department of Energy Technology, Aalborg University, Pontoppidanstraede 101, Aalborg DK-9220, Denmark.
2.Vlaamse Instelling voor Technologisch Onderzoek, unit Energy Technology, Mol, Belgium;
3.Vrije Universiteit Brussel, Mobility and automotive technology research group, Brussels, Belgium;
*Corresponding Author
Tel.: +45- 99 40 33 74; Fax: +45- 98 15 14 11.

ABSTRACT: The paper investigates the potential of using lumped stationary battery energy storage systems (BESS) in the public low-voltage distribution grid in order to defer upgrades needed in case of large penetration of electric vehicle (EV), electrified heat pump (HP) in presence of photovoltaic (PV) panel on the view of techno economic optimal sizing taking the consideration of season-based diurnal dynamics. The BESS is primarily dimensioned for the peak shaving operation targeted for the counterbalance of overloading of transformer; BESS also participates in arbitrage (buy low, sell high) application. The paper assesses the effects of a PV-BESS combination and the control of such a system with the help of a newly devised season specific BESS control protocol that ensures the availability of energy for peak-shaving purpose (namely peak period in winter) and it participates in arbitrage. The objective of this paper is to develop and detail the method of optimum sizing energy storage for grid connected distribution systems using newly devised BESS control protocol and investigate its sensitivity to factors which are known to influence energy system performance and hence storage requirements. The results provide insight into the dimensioning and the required specification and configuration of BESS.
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Keywords: Batteries; Battery storage and Control; Economic Analysis; Grid Integration; Grid Control; Grid Management; Large Grid-connected PV systems; PV system

1 INTRODUCTION

With ever increasing emphasis on providing customers with a capable and cost effective network, there is considerable pressure on network planners to provide optimal network solutions such as BESS to cater for both the existing load and anticipated load growth. The potential of BESS to support the operation of public distribution grids gains wide attention [1,2]. Conventionally, storage systems in combination with solar panels are large systems to bridge many-day periods but the purpose of this paper is to find the optimal storage for satisfying daily energy dynamics. Recently, BESS technology is becoming cheaper as technological advances while the energy cost is rising. Although, BESS technologies are growing fast, there are many open questions regarding the optimal design, scheduling and control of such systems. This is mainly due to the complexity imposed by the availability of many different technologies and the special requirements of each specific installation, such as the geographic location of the BESS system around the globe, power demand profiles, electricity pricing policies etc [3,4]. Storage devices will have investment and operating costs in addition to finite life time. A special instance of the problem where a single centralised BESS unit is installed in the neighbourhood is considered. BESS consists of multiple battery-cell energy storage (set of battery cells with matching inverter-converter configuration and management system) units connected to the utility single phase transformers' 240 V secondary and assumed to be controlled from a designed local controller for optimum energy flow(section 5.5) of the storage. Sizing a BESS device too small may either reduce its operating life through over use, such as exceeding maximum depth of discharge too frequently [5], or render it ineffective for the required function (in the paper peak shaving). Sizing a device too large will result in increased capital costs which will increase the cost of supplying energy, therefore, effective to solve grid problems yet efficient storage sizing is indispensable. The individual stationary BESS unit can be placed in close proximity of transformer and typically be deployed in Underground Residential Distribution (URD) settings adjacent to a single phase transformer. If the load level is in such position that the energy required by the load is larger than the predefined allowed level of transformer, then the battery pack meets the deficit given that the battery has not reached its desired depth of discharge. In order to keep costs at a minimum, the size requirements for energy storage devices must be determined to harness the maximum profit out of the BESS for a reasonably decent lifetime. Two electrical storage technologies are taken into account: lithium-ion and lead-acid technologies. Optimum system configuration is identified based on the minimum cost of BESS through optimal dispatch energy flow strategy of candidate BESS. It is important to study the optimal grid power flow to schedule battery charge–discharge from the system operation point of view within certain lifetime of operation. In a distribution power system where the BESS is considered as an option, the design objective is to obtain the ratings of the battery package required to meet a given load profile pattern considering PV penetrations and the economics of the charging and discharging. Generally PV is curtailed from the distribution system when the voltage level and active power level of PV exceeds certain limit as stipulated by national or regional power regulators. To hedge losses due to the curtailed energy can be stored in batteries indoors [6]. An implied prospect to curtail injected power is a feed-in tariff (FIT) supporting self-consumption, that gives an incentive to install batteries [7,8]. In several countries, such an incentive system already exists (e.g. Germany). A combination of multiple services with a single BESS has been suggested in [7]. A simple BESS model was used to demonstrate the possible trade-offs between benefits for stakeholders. [9-11] proposed distributed BESS system to alleviate grid related issues. Energy management goals are defined as to be economically optimal for daily basis while taking into account technical constraints of BESS. An alternative approach is to install batteries at locations where a PV inverter is already present for example inside the home [7,11]. A second alternative is to use the batteries of locally parked electric vehicles through the vehicle to grid concept [12].

2 BACKGROUND

The ever increasing load demand originated from the usage of different modern household devices e.g. electrical heat pump and electrical vehicles by the consumers poses moderate to severe stress on the distribution grid. Generally, the current distribution grid is designed in a way that the power rating of the grid infrastructure is larger than the maximal expected peak power demand in order to take into account a future increase in power demand. So the introduction of a small number of large loads like electrical vehicles or electric heat pump within one typical neighbourhood will not immediately lead to problems with the distribution grid infrastructure. However, as the number of these big loads (e.g. high penetration of electrical vehicles, several heat pumps) increases, it is more likely that certain problems will start occurring such as an increased peak power through the distribution transformer. For example, since most owners of an electric vehicle require that their car charges overnight to be fully charged in the morning and most electric vehicles can possibly be plugged-in at approximately the same time in the evening, a large peak load occurs on the grid in the evening which can be added with a fully operational heat pumps in a cold evening. In addition to this, the peak load from the electric vehicle might coincide with the traditionally present residential evening peak power demand. When the power peak exceeds the rating of the transformer, infrastructure investments have to be made in order to be able to accommodate the high power and high energy load. The occurrence of an exceeding power peak will happen more often in neighbourhoods with a high penetration of electric vehicles and in dense distribution grids, As the number of these big loads (e.g. high penetration of electrical vehicles, heat pumps) increases, certain problems will start likely occurring such as an increased peak power through the distribution transformer [1].The goal of the paper is to find the cornerstones for sizing for the BESS used to alleviate grid related issues. For a representative scenario, a grid operator can decide to temporarily install a BESS in problematic feeders, in order to postpone grid upgrades in the short term due to the work scheduling matters, the battery system can be stored in containers with the necessary installation equipment. The container can be movable to bring it whereas the system is necessary. When the grid operator compares the cost of grid upgrades, it is possible that the BESS is a valuable alternative in the short term or even in long term conditions. Since the BESS is grid-connected it should not necessarily cope with a long period of PV production or long term load profile variation, as the grid is available as a back-up. Storage can be introduced in account of absorbing the PV production surplus while operating in summer. For grid connected storage the size can be smaller because a daily dynamics of the storage is sought for [2]. The effectiveness of grid connected storage can be reflected in the amount of benefit that can be gained after deployment of BESS. Another factor depending on the storage system is the maximum investment a financier wants to make for deploying BESS. In this case, a maximum size of BESS is also obtained. The BESS is designed for a 24 hour time horizon. The objective is the optimal selection of the system components among several candidate technologies (Li-ion and PbAc technology); including the optimal design of BESS that allows energy exchange among the grid and BESS.

3 METHODOLOGY

A methodology to obtain the system sizing for BESS system for a given load profile encompassing of EV, HP and household data, PV generation power profile and tariff systems to generate feasible design space is discussed in this section. The proposed method is structured of two stages. The first stage sets limits the options for storage size stemming from different allowable transformer loading level, then the second stage optimises for BESS operation within technical and economic limits considering daily dynamics. The allowable transformer loading level limits the peak loading of transformer i.e. the threshold of power level in transformer from where the peak shaving operation is needed to be carried out. It is basically by supplying a reasonable range of storage energy ratings coming from maximum allowable limit of loading of transformer (this effectively set the minimum BESS size constraint) and then by iteratively feeding all the possible combinations of storage energy market economics data as well as different technical constraints into the optimisation stage for determination of optimum power flow considering daily dynamics. Then the optimised power-flow stage the operation and overall cost of the energy system in a year is calculated and a numerical search is performed to find the lowest cost of the candidate sizes and the lowest cost size corresponds the optimal sizing.

In a linear programming [3] exercise, all the participating information and corresponding constrains of a specific time period is available, the algorithm is able to optimise the power flow of the battery given that the price profile and load profile is given beforehand. The motivation of linear programming optimisation is in the fact that a single method can incorporate the technical constraints of a real system and the correlations between input data sets while producing a lowest cost solution.

However, in the real control of a PV-BESS, there is only limited knowledge of the future's weather and the electricity demand. Therefore, it should be tested how close a control algorithm can attain to the optimum i.e. baseline scenario. In order to test and benchmark the method, a time-series adjusted load profile is developed. As because the available raw data has different resolution and length, in order to provide conformity for finding a uniform representations a unified filtering method composed of two filters is applied. The requirement of a desired storage period of 24 hours is sought. Load profiles are offset from non-curtailed PV data and actual load profile to integrate for the effects of diurnal correlation. Finally, sensitivity of sizing to buying and selling costs, maximum allowable transformer loading level, average difference between buying and selling costs of BESS are examined. The optimisation stage is provided with BESS nominal energy constraints and then outputs an optimal value of charging discharging power of BESS based on the determined scenario constraints representing optimal power flow (OPF) of the BESS. This is repeated until all the possible combinations of the storage combinations have been executed. The lowest overall cost (operating and capital costs) originating from a numerical searching of the BESS is the optimal size of the battery pack. The system operating cost is determined for the optimal power dispatch of the battery system. The controller decisions are based on the energy balance and the operating limits of the various components of the energy system.

The optimal dimensioning procedure is figuratively shown on the Figure 1.

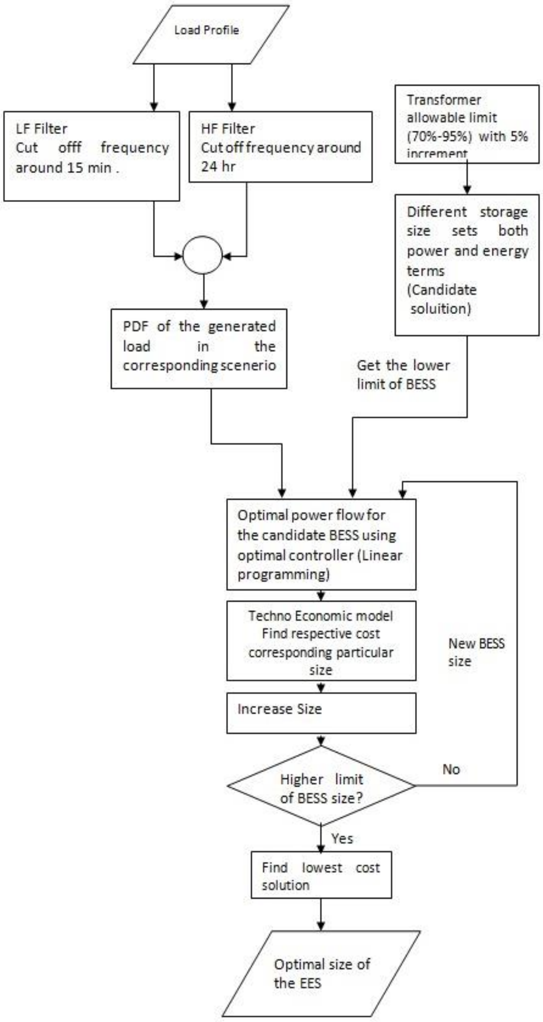

Figure 1: Flowchart of the dimensioning steps.

4 GENERAL ISSUES AND ASSUMPTIONS

This method requires synchronized time series of all data related for dimensioning (e.g. load and PV data). In this paper synchronization means the data sets are of the same resolution and used data sets are assumed to capture seasonal and hourly correlations between load power and PV. A load flow analysis is implemented in MATLAB®. A constant power load state model is assumed. In the load flow calculation, the voltage drop between different grid feeder levels is not taken into account.

Three representative days of three different seasons are picked for following candidate sizing solution. The optimization method is applied to representative reference scenarios of a LV distribution feeder.

The intermittent resource data is converted into units or equivalent of power rather than being left as resource units like irradiation of solar. Although in different season the battery system performances can be varied, but in these cases an isothermal environment with uniform performance is assumed meaning the battery system behaves in the same manner on different weather condition on the whole simulated period. Furthermore, in practice, a short term and long term control method would be required to operate the BESS. The short term control method controls the BESS power flow and performs the battery state of charge estimation [4, 5]. For the implementation of long term control, rule-based method has been proposed in this paper. The resolution of the data sets used is quarter-hourly.

A mathematical linear programming model is developed that optimizes the power flow batteries in the network given the constraints of diverse energy components and tariff rates. The employed method is generic in the sense that nearly all time dependent tariff structures can be included without losing accuracy, but obviously to gain benefit from arbitrage the differential electrical price is prerequisite and is used (*section 5.2*). The outcome of this paper results will be largely affected by the local tariff structures in use. The amount of PV energy when the PV production power exceeds the load power in the neighborhood, then excess amount of PV is referred as curtailed energy in the paper.

The optimal BESS control strategy is determined under the hypothetical assumption that all information (e.g. electricity price, load profile etc.) is previously known and deterministic. This has been done to obtain a lower limit on the daily electric energy cost composed of arbitrage participation cost and the cost regarding to alleviate loading level of transformer. The optimization is mainly based on a given, country dependent, time variant electricity tariff structure, the load profile and the PV power data over a year. In this paper, the regular battery manufacturer definition for battery lifetime is used: battery systems are replaced when the usable capacity falls below 80% of the nominal capacity. A replaced battery is still usable with a reduced effective energy capacity. Therefore, the estimated calendar life in the results is underestimated [6]. If the batteries were to be replaced at 80% of the nominal battery capacity, there may still be a second life capacity. If this case is incorporated in the proposed model the battery system cost is overestimated [5]. Based on the proposed approach, for a given load demand and energy system characteristics, a modified adjusted load can be built upon which is used to determine the cost effective solution for BESS operation. The typical summer sunny day can lead depending on the installed PV production capacity to have an excess PV production during midday. This leads to the obvious conclusion that by charging in the BESS using the excess PV production can be used in times when the electricity demand exceeds the PV production (curtailed power).

The results of the distribution grid are based on the cumulative data of 160 Belgian households with its own typical correlation between production and demand. Since the correlation factor can have an impact on the results obtained from the dimensioning the applicability of the results is limited to regions with the same typical climate. In order to capture seasonal correlations, data sets are taken on the representative days for the corresponding seasons (summer, midseason and winter) [3]. The model is split into three separate representative days. The primary assumption in that case is that these representative days of different season can be simulated with mean and standard deviation (i.e. Gaussian distributed) for aggregation to get the yearly load. The results from each period are compared and the largest storage size that provides minimizes the cost is selected.

5 MODEL FORMATION

The following sections elaborate different model steps used in the simulation.

5.1 Load profile modeling

The appropriate load models which capture the real world load variations would serve as a valuable input for the design of BESS and would yield a robust system design. Load curve in a typical distribution network location exhibits a varying demand profile. Essentially generic load profiles simulate the approximated loads. The accuracy of the simulation is obviously limited by how closely the generic load profiles match the actual profiles in the network. The derived load profile, scaling factor and power factor for the load effectively compensate for any errors in the assumed generic profiles applied to the aggregated load categories.

The main reasons of varying load profile variations are [7]

- Climate state: the season, the daily temperatures, the speed of wind etc.
- Demographic aspects: the growth rate of the population, the number of the inhabitants of the certain area, the birth rate, etc.
- Economic features: the gross domestic product (GDP), the labor productivity, the economy development rate, the level of life.

The evolution in time of all these parameters has a strong random character. At a certain moment, the more or less accidental realization of these parameters directly influences the load and its variation tendency change influences in a decisive way of the load curves. The shape of the load profiles usually describes a daily and weekly periodicity. However, the load profile for tomorrow or for the next week is not just a simple copy of the load profile from today or from this week. Instead, the load profile is slightly modified from day to day and from week to week, to reflect changes in consumers' behavior or weather conditions. For grid alone systems, transformers are sized based on the expected peak demand. Methods of sizing energy storage devices are largely dependent on the load profiles of the energy ecosystem in distribution grid to be modeled. In order to determine which capital expenditures have to be made for the distribution grid to be able to handle the circulating power levels of BESS system, the maximal gap between local supply and local demand has to be derived. So a representative load profile is very important to simulate the distribution grid system. One option to get a representative grid model is a bottom-up approach, where several typical house is modeled, including its generated power (e.g. via solar panels) and power consumption.
Photovoltaic units can be placed in all buildings, but upper bounds are posed on their sizes, due to the limited available area in each building and the particular energy regulations of individual countries. The total surface of PV panels installed in each node cannot exceed an upper bound, which is indicated by the dimensions and other characteristics of the building or by energy regulations.
A generalized single EV and HP load electric profile with necessary random scaling factor with aggregated EV and HP profile data is used.
In the end all these household, EV and PV data are summed and scaled from the household level to transformer level. The adjusted load profile will be regarded as the load profile of the transformer.
An adjusted load profile is illustrated on Figure 2.

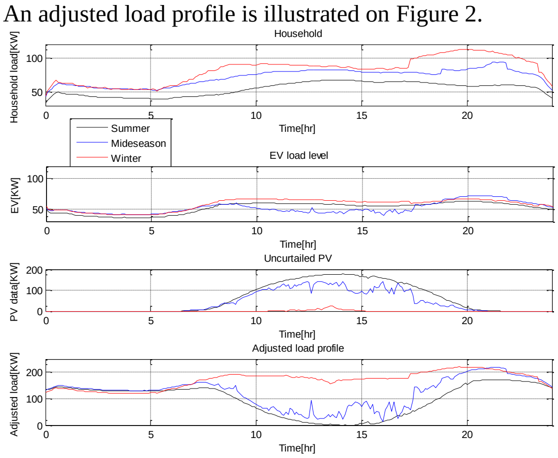

Figure 2: Adjusted load profile generation of different season profiles [a]household data [b]EV load level[c] non-curtailed PV power [d]Adjusted load profile considering [a],[b] and [c].

It is important from designers' perspective to identify all the feasible combinations for the rating and the corresponding storage capacity. The simulations to obtain the minimum storage capacity are carried out for different values of the allowable transformer loading levels. The performance of a distribution grid BESS is affected by the magnitude and frequency of variations in adjusted load profile. For instance, diurnal variations affect the amount of energy storage required to ensure reliability throughout a day. In the same way, seasonal variations affect the amount of long term storage required to balance out energy over the season. The specific method filters are required for the capturing the magnitude of variance at vital frequencies, such as diurnal cycles, that uses the magnitudes on 24 hours to size energy storage requirements. Filtering adjusted load profile variance requires a filter function of two filters one low pass filter and other high pass filter. Two different filter functions are used as derived by [8]. The filter is used for the load profile to isolate: the long term variance or store period average variance, the short term variance. These filters characteristics are shown in Figure 3.

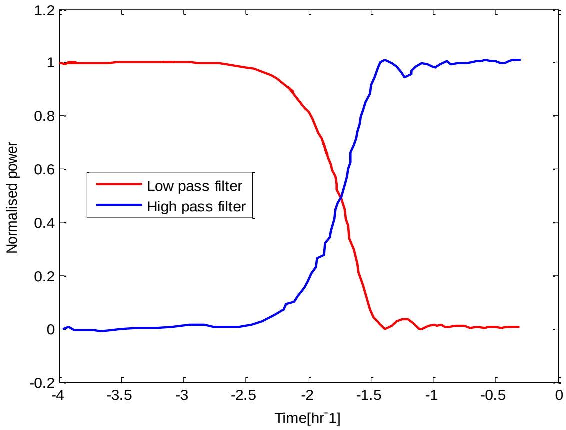

Figure 3: Filter Characteristics curve [time in logarithmic scale [hr^{-1}].

The usage of the filter is due to the fact that different acquired data have different resolution and to make the data filtered in same frequency level. The proposed method draws on purely statistical information namely probability density functions (PDFs) of load profile and average and variance to determine diurnal load levels. The method proposed first utilizes the mean and variance of a data set to construct a PDF (for example, from a time series of adjusted load profile with PV). This PDF gives the probability of an average particular load level and its variance. This method calculates a periodic variance in an attempt to capture the effects of variable load. In the paper three levels of yearly data are divided such as midseason (autumn or fall), winter, and summer.

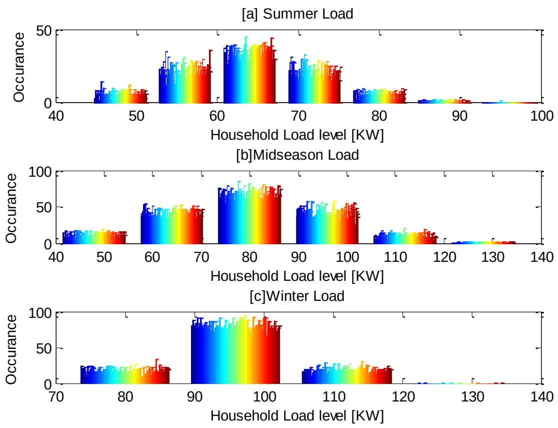

Figure 4: Distribution of the occurrences house hold level in different season.

The filtered short and long term variances are utilized to determine probability density functions of load profile, these load profiles can be used for load flow analysis. At each cell the system's operating state is calculated based on the distribution network load level. These include values for load power, grid power, charging-discharging powers, PV power, EV power etc. The final result is the available power commitment and the expected values of energy entering and leaving the storage using OPF. It is assumed that the load is recurring in the same Gaussian pattern in a season. For household data the distribution curve can be found in Figure 4 and Figure 5.

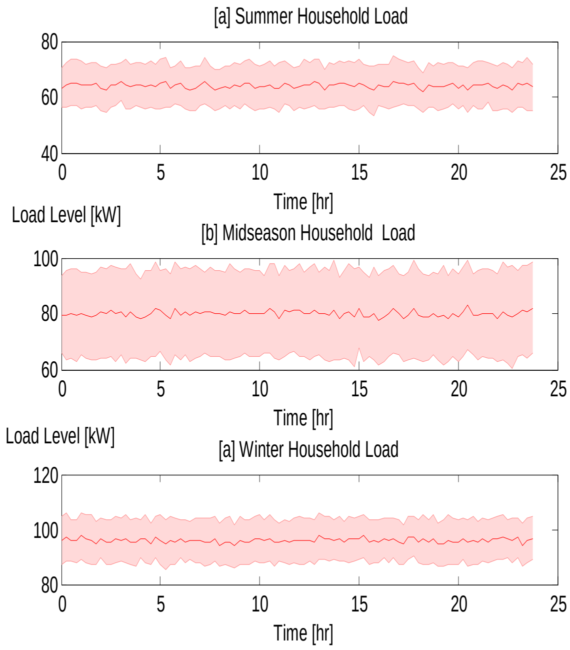

Figure 5: Tariff rate used in the simulation

5.2 Market model

The current cost of electricity storage limits deployment opportunities to resolving site-specific issues. Market predictions indicate that near-term costs for electricity storage may broaden deployment opportunities. Fluctuating electricity prices that may lead to attractiveness of charging a battery partly by grid electricity but in that case BESS needs a good control mechanism to gain the benefit from differential price. A dynamic electricity tariff is enforced for the sale of the electricity based on the baseline scenario defined in [9]. The electricity price profile m_i is given by,

$$m_i = (0.44 + 0.56\bar{m}_i^{\mathrm{BPX}}) * 0.18\ldots\ldots(1)$$

Where, $\bar{m}_i^{\mathrm{BPX}}$ is the normalised wholesale price at time step i on the Belpex day-ahead market for electricity of 2008 [10]. The fraction 0.44 represents the constant distribution costs (0.35), transmission cost (0.08), levies (0.01). the fraction 0.56 represents the variable energy cost [9]. The income from selling electricity back to the grid is calculated based on the cumulative amount of electricity delivered back to the grid and load. The model gives the option of using dissimilar buying prices from the electricity grid. The buying price of the electricity is not subjected for constant distribution cost rather it consists of variable electricity price (0.86), transmission cost (0.125), and levies (0.015).

Buying price from the market for the BESS operator is,

$$m_k = (0.14 + 0.86\bar{m}_k{}^{\text{BPX}}) * 0.18\ldots\ldots(2)$$

The tariff structures should be regarded as *corner case* tariff structures since government incentives have been omitted. The tariff rate that is used for the simulation is shown figuratively in Figure 6.

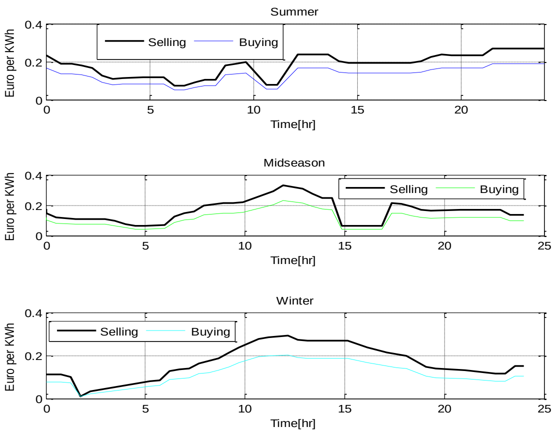

Figure 6: Tariff rate used in the simulation.

To enhance the motivation of the peak shaving, the marginal congestion price of electricity is needed. The marginal congestion price is not the mean kWh price, but the price of an additional kWh consumed given that additional power crosses the allowable level of the transformer. The marginal price is needed since for large consumers in some countries a digressive tariff is applied. In order to be able to contribute on peak shaving using BESS to avoid over-load of the distribution grid, marginal price is included because mitigation of BESS is not achievable without compromising the energy stored by the battery. These market model is needed a good insight by an optimization algorithm. Marginal Electricity price in different cities are shown in Table I.

Table I Marginal Electricity price in different cities.

City	*London*	*Berlin*	*Antwerp*
€c/kWh	13	19	18

5.3 BESS Model

BESS is capable of providing active power directly to grid as required. The bidirectional power flow P_i from battery is split into two positive opposite variables: the charge power P_i^c which correspond power toward battery and the discharge power P_i^d which corresponds power extracted from battery. The amount of energy which leaves the storage must be supplied by energy entering the storage. Thus these two terms are set equal to each other which affect both charge and discharge power, it is used to balance charge and discharge energy with corresponding charging efficiency, η_{char} and discharging efficiency, η_{disch}. Energy storage in distribution grids is primarily bounded by two factors: discharge time and power rating. Consequently, energy content in each time step of the optimization is limited by a minimum E_{min} and maximum state of charge E_{max} and evolves from previous time steps by the mechanisms of charging and discharging. The following equations govern the storage device power state, P_i at time instant i,

$$E_{min} \leqslant E_0 + \Delta\text{t}\sum_{i=1}^{t}(P_i\eta_{\text{char}} + \frac{P_i}{\eta_{\text{disch}}}) \leqslant E_{max}; \forall i \in 1,2,\ldots.t \quad \ldots\ldots(3)$$

5.4 Constraints

Detailed constraints ensure the model closely replicates real world conditions that represent the operation of the BESS. Extending the basic model formulation, some additional logical constraints are presented in this subsection, which can be used to meet some special requirements in the design of the BESS in distribution network. These constraints further restrict the search space and in general their inclusion in the model increases the optimal value of the objective function.

» Ramping constraint and charging discharging efficiency

The method assumes a simple storage device with homogeneous ramping constraints and which can be characterized by the uniform charging and discharging efficiencies over the simulation horizon. The coulomb efficiency is included in the charge efficiency parameter. Therefore, the value is less than the discharge efficiency. The efficiency is modeled as independent of current and temperature.

» Self-discharge loss

The self-discharge loss for the battery is assumed to be negligible and not accounted for.

» Power threshold of batteries

The maximum charge and discharge power is dependent on the battery technology [shown in Table II].

» Grid interaction constraints

The following constraint does not allow a node to purchase and sell electricity from/to the grid during the same period. This constraint is necessary in cases of high prices of selling electricity to the grid, due to promoting renewable energy strategies. So, P_i^d and P_i^c have cannot have two nonzero values at time instant i.

» Depth of Discharge limit of BESS

Energy content in a lot of cases is restricted to a chosen limit on depth of discharge because cycles of high discharge can cause premature aging of the cells depending on battery chemistry.

» Energy level of BESS

A premeditated initial energy level (E_0) of BESS is chosen in this paper. As the optimization start time at middle of night and normally there is no load to consume and the price is in all the scenarios all are low. In that case the initial energy level of battery is full that will necessarily change the result negatively and in most cases the initial condition is chosen so that the battery can get full benefit of assumed lower price of lowered night tariff. Continuity is assured with events preceding and following the current time span. The constraint governs the final state of the storage system.

Initial Energy level of BESS, $E_0 = 0.001 * E_{\text{eff}} \dots \dots (4)$

Effective energy of BESS E_{eff} = E_{max} - $E_{min} \dots \dots (5)$

Final Energy level of BESS, $E_t = E_0 \dots \dots (6)$

In addition, it is imposed to resume, at the end of each day, the initial batteries state of charge is identical to the end of day state of charge. This last constraint is properly introduced with the aim of making the days independent of each other, leading to a reconfigurable daily planning procedure. The battery energy has to be between the rated and minimum values depending on the allowable depth of discharge. The peak load occurring in the afternoon and the evening is met by the grid and the BESS system together by parallel operation. The battery energy state falls to its allowable minimum by the night time. The BESS goes to the charging mode as the cycle repeats.

» Calendar and cycle life of BESS

The battery calendar lifetime is regarded as the lifetime independent of the usage of the battery.

5.5 Optimal power flow control of BESS

It is essential to study the optimal grid power flow to schedule battery charge–discharge from the system operation point of view within certain lifetime of operation. The design variable is the battery power flow P_{i} in order to minimise costs for the power flow of BESS. Optimum Power Flow for BESS operation in this paper encompasses multiple time steps (24 hours) at once. In case of the storage power flow, the individual time steps are no longer independent. Under the constraint, the energy is extracted from the battery only and only if it is cost effective. The control strategy is defined as a virtual cost found in optimization only that has to be paid for draining energy from the battery. Incorporating these virtual costs in the optimization problem results in an effective wear protection, the battery will only be drained if it is cost effective enough compared to the virtual draining cost. This is important if, for example, the number of drain cycles is limiting in a day. In a tariff structure with a high frequency component this will become relevant. In the proposed methodology, the power dispatch is optimized so that the system operates under the most cost-efficient condition.

The algorithm for finding optimum power flow is formulated as [11] with modification. The structure of the whole cost function formulae is that it is made with a series of linear equation,

$$\min_{P_i}\left[\Delta \text{t} * \sum_{i=1}^{t^{max}} \{P_iC_i + \alpha_1 * \max(0, P_i - P_{Th}) + \Gamma * \lambda_{BESS,i} * max(0, \min(P_i, \tilde{P})) - \delta_{\text{ij}}(C_i + C_{m,j})P_i\}\right] \dots \dots (7)$$

In this Formula, the meaning of the symbols is the same as in *Eqn.* (6).The first term represents the BESS availability for arbitrage. C_i is added as a power exchange price curve *(see* Figure 6*)*. The solution to this optimization problem maximizes the aggregated revenue of all BESS units. In this simulation $t^{\max}$ has 24 hour value and Δt is equal to 15 minute. By setting and updating the state of charge for BESS at based on the corresponding battery power values the optimum power profile is sought using linear programming. The second term, $\alpha_1 * \max(0, P_i - P_{Th})$ is associated with the penalizing cost of BESS system that operates above its threshold level,P_{Th}. α_1 is a virtual cost assigned to the BESS system for exceeding the threshold level of the BESS P_{Th} that is battery specific. A high price 0.30Euro (30 Euro cent) is provided for α_1 on three seasons. That ensures larger price penalty for crossing the threshold. The third term $[\Gamma * \lambda_{\text{BESS,i}} * \max\left(0, \min(P_i, \tilde{P}\right)]$ represents the power reserve in case of known future overloading on transformer. The term is associated with the future cost saving if the BESS discharge not in the optimizing time instant. Γ is boolean variable that enables the future cost saving option (works like an enable switch). At first the deficit of the transformer is calculated using the formula given in Eqn.(8).

$P_{\text{def},k} = E_k - E_{\text{ref}}; \dots \dots (8)$

Average power needed for supplying deficit of energy, $\tilde{P} = \text{avg}(P_{\text{def},i}) \dots \dots (9)$

Total amount of energy deficit,

$E_{\text{def}} = \sum P_{\text{def}} * \Delta \text{t} \dots \dots (10)$

Γ is provided zero, when there is no peak loading of transformer (total peak load is less than maximum overloading of transformer as well as current energy level of BESS as well as E_i is more than energy deficit, E_{def} and provided 1 when there is really peak loading problem or congestion (in other cases).For example, in the simulation case at summer transformer does not face congestion and Γ is 0. $\lambda_{\text{BESS,i}}$ is the future cost saving factor. It depends on the average current electricity price and the marginal congestion electricity price. The equation to find λ_{BESS} is given by,

$$\lambda_{\text{BESS,i}} = \frac{\sum_{j}^{no\_ov\_pulse} (C_j + C_{m,j}) * P_{\text{def},j}}{\sum_i^j C_i * P_{\text{def},i}} * T_{ov} \dots \dots (11)$$

C_j is the cost at the time instant and $C_{m,j}$ is the marginal price at the instant (*j* is the index that signifies transformer overloaded) and T_{ov} is the overloading time[in hour] of the transformer. $\sum_i^j C_i * P_{\text{def},i}$ counts the total cost from current index, i until the congestion index, j price of energy. The numerator factor

$\sum_{j}^{no\_ov\_pulse}(C_j + C_{m,j}) * P_{\mathrm{def},j}$ gives a higher price in order to reserve the energy for future use. The motivation is that if BESS power flow there will be additional risk that it cannot be able to provide the required power when peak shaving application due to participating required arbitrage phenomenon. So it is important to have larger price on peak shaving application price than that of arbitrage to execute the controller to react on peak shaving application. In case of unavailability of this higher peak shaving price the controller works sub-optimally and does not reserve the energy for the future application. The last term $\delta_{\mathrm{ij}}(C_i + C_{m,j})P_i$ ensures the cost reduction of the power level when the transformer is overloaded. δ_{ij} is the Kronecker delta function that ensures the term is activated only when the transformer is overloaded and the battery has not reached its constraints. The usage of negative sign signifies the cost reduction of providing the energy at the overloading time. The grid operates by meeting the load and simultaneously charging the battery bank and bringing it to fully charged condition while the purchase price is low given that the BESS constraints permit. For every size of battery OPF finds the best optimum charge power P_i^c and optimum discharge power P_i^d.For each evaluation of a candidate size, the OPF algorithm is executed until the minimum cost solution is found that satisfies optimum power constraints.

» Electricity balance constraints

The optimum dispatch, P_i^c or P_i^d using OPF algorithm has been determined satisfying the load balance conditions and charge constraints that ensure the load is always met, that the storage is operated correctly and that energy is utilised. Electricity demand is satisfied by electricity produced by the BESS unit as well as by purchasing electricity from the grid .The demand constraint balances load at each iterative time step, i

P_{load}=P_{grid}+ P_i^d-P_i^c … … (12) ; P_{grid}=power extracted from grid

5.6 Annual cost of energy calculation

The result of OPF (P_i^c *and* P_i^d) is inserted into the cost model to calculate the annualised cost energy of the candidate battery technologies. Battery costs depend on the required ratio of power-to-energy, which depends on the battery chemistry [12]. The investment cost is determined by the battery pack sizes and the corresponding management and peripheral costs; also the number of battery replenishments is included, based upon the number of drain cycles, and the assumed maximum number of drain cycles. The equivalent annual cost model is used for capital budgeting. To compare the financial costs of operating each method’s proposed energy system, an annual recovery factor method is used. Total investment cost is converted into annuity. The assumption is each year equal amount of money is introduced for calculating per annuity of the investment using capital recovery factor. The cost of the storage system is converted to an annual cost and added to the system operating cost, yielding a yearly cost of energy.

$\min(C_{\mathrm{Total}})$ for finding the optimum size of the battery.

$$C_{\mathrm{Total}} = C_{\mathrm{inv}} + C_{\mathrm{op}} + C_{\mathrm{Grid}}^{\mathrm{Pur}} - C_{\mathrm{Grid}}^{\mathrm{Sale}} \ldots \ldots (13)$$

The effective cost of energy (*COE*) per year, C_{Total},which accounts the annualised capital cost, C_{inv} of amortisation period, t_a , the operating costs C_{op} associated with the system. CRF is the capital recovery of the system, C_{BESS} represent per unit capacity cost of the battery.

$$C_{\mathrm{inv}} = \frac{\mathrm{CRF} * C_{\mathrm{BESS}} * E_{\mathrm{nom}}}{t_a} \ldots \ldots (14)$$

A capital recovery factor is the ratio of a constant annuity to the present value of receiving that annuity for a given length of time. Using a discount rate r the capital recovery factor is given by,

$$CRF = \left(\frac{1 - 1/(1+r)^{t_a}}{r}\right)^{-1} \ldots \ldots (15)$$

This approach then results in an annual expense for each investment which can then be compared. The calculation above is a variation of the annuity calculation as given in [13]. $C_{\mathrm{Grid}}^{\mathrm{Pur}}$ is the annual purchase cost of electricity estimated system and revenue, $C_{\mathrm{Grid}}^{\mathrm{Rev}}$ is determined by the total annual energy delivered by BESS system; both are based on optimum energy flow into the battery. For any particular season s in a particular day d the total number of charge pulse, $\mathrm{n_{ch}}$ and discharge pulse $\mathrm{n_{disch}}$ then buying cost $C_{\mathrm{Grid}}^{\mathrm{Pur}}$ and selling cost $C_{\mathrm{Grid}}^{\mathrm{Rev}}$ are calculated using the following formula,

$$C_{\mathrm{grid}}^{\mathrm{Pur}} = \sum_s \sum_d \sum_{\mathrm{n}_{ch}} (P_i^c * C_i^c) \ldots \ldots (16)$$

$$C_{\mathrm{Grid}}^{\mathrm{Rev}} = \sum_s \sum_d \sum_{\mathrm{n_{disch}}} (P_i^d * C_i^d) \ldots \ldots (17)$$

6 SIMULATION CASE ANALYSIS

The research focuses on a hypothetical Belgian neighbourhood in the year 2020, having an assumption of no connection to the gas grid for heating or cooking purpose. The electricity demand without HP in the grid is composed of 16 % electric cars, 11 % electric cooking, and 72 % remaining household applications.The proposed scenario uses a 230V reference grid, based on the topology of a real semi-urban feeder. The grid frequency is 50 Hz. The neighbourhood is formed by 160 houses. The houses are divided over four A1 feeders connected to a 250 kVA (10 kV: 0.4 kV) transformer. A constant power factor of 0.90 is assumed. A single-phase PV generation profile is assigned to 40 of 160 houses, corresponding to a PV penetration level of 25 % having the peak level between 2-10kWp. Because of the correlation between PV generation profiles of nearby houses, only one single PV profile is used (using necessary random scaling to include effect of different size). VITO acquired household data is used with above mentioned method. For all cases, the household profile and PV generation profile are combined into one net power profile. The HP and EV data originate from different VITO measurements with possible scaling factor to take into account of the sizing. The set of BESS model parameters is used in simulation shown in Table II in line with commercially available products as used in [5].

Table II: The battery parameters for the simulation scenario.

Attributes	*Li ion systems*	*Pb Acid systems*
Cycle life	1500	500
Charge efficiency, η_c	90%	80%
Discharge efficiency, η_d	98%	98%
Nominal Energy Specific cost of the battery system, C_E^{bat}	1000€/kWh	400€/kWh
Battery peripheral lifetime	10 year	10 year
Shelf life	25 year	10 year
Allowable DoD	80%	50%

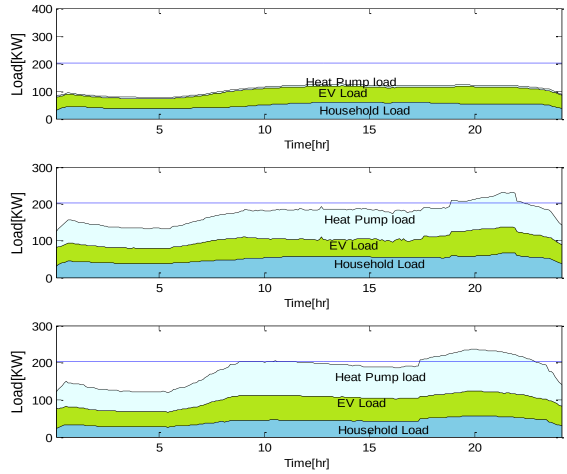

Figure 7: Load level of the distribution transformer in winter. Blue line represents the rated allowable level on the transformer.[Top]Summer [middle]Midseason [bottom]Winter.

Two currently available technologies are considered: lithium iron phosphate (Li–ion) batteries and absorbed glass mat lead–acid (PbAc) batteries. A standard transformer of 250 kVA will be overloaded in winter and midseason when the gas fired boilers are replaced by electricity temperature controlled HPs, during winter and midseason days that are shown in Figure 7. The aim of deploying BESS is to avoid these overloading conditions while participating in arbitrage application.

The demand and supply are extrapolated over the year of 2020 and yearly calculation is based on 2020 calendar in Table III.

Table III: The yearly calculation is based on 2020 calendar.

Season	*Summer*	*Mid Season*	*Winter*
Timespan	June 21- September 21=92 days	March 22- june 20 September 22- December 21 =180 days	December 22 –March 21=89 days

The result of the simulation of optimum power flow is shown in Figure 8.

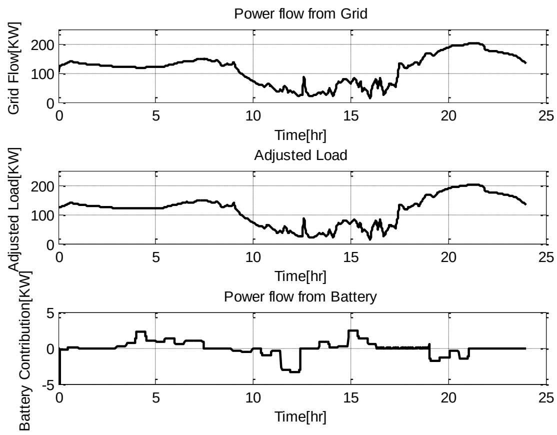

Figure 8: Load flow result for the midseason (autumn/fall) time PbAc battery system.

It can be seen that during summer demand is supplied by PV production, the excess PV production is stored in the battery which in turn is drained in the time when it is needed. In summer BESS is charged up by the excessive PV energy. The evolution of the battery pack state in the simulated case can be observed in Figure 9. It is observable that the battery system discharges at different times obeying the restriction optimum power flow condition. In midseason the price of electricity shows variability around afternoon and the battery pack system makes an attempt to lower charge-discharge cycle while responding to the peak shaving in the evening. Total BESS investment length is chosen to be 10 years, therefore, amortisation period, t_a =10 year. In the paper Antwerpen's marginal price is used for simulation purposes and discount rate r = 5% is used. The annual operating and maintenance cost of the system (C_{op}) has been taken as 10% of the capital cost. If the size of the BESS is small it needs less money to charge but the total revenue accumulated is also low due to the lowered capacity. The price of electricity at the time of overloading (peak shaving period) is taken higher so that BESS can perform discharging in a good monetary incentive. On the other hand if the size of BESS is bigger it is expensive to charge the BESS system, due to the large size the fixed cost share is also bigger. In winter times it can generate also higher revenue but due to fixed cost and increasing charging cost bigger size corresponds to the increasing costs. In case of optimum the size is large enough to get sufficient revenue as well as maintaining the minimum fixed cost as less possible. The size must correspond to the required energy that the transformer is not overloaded. The BESS that is functional that requires at least 280 kWh deficits to meet the peak loads in the winter if the allowable limit of loading level is assumed to be 85% of the maximum KW rating of transformer. The aim is to find the optimal BESS size that can offset as much as the peak shaving and to get maximum amount of monetary benefit in terms of the whole year cost of energy consideration. The optimum size corresponds to 350 kWh and 560kWh for Li-ion and PbAc technologies respectively.

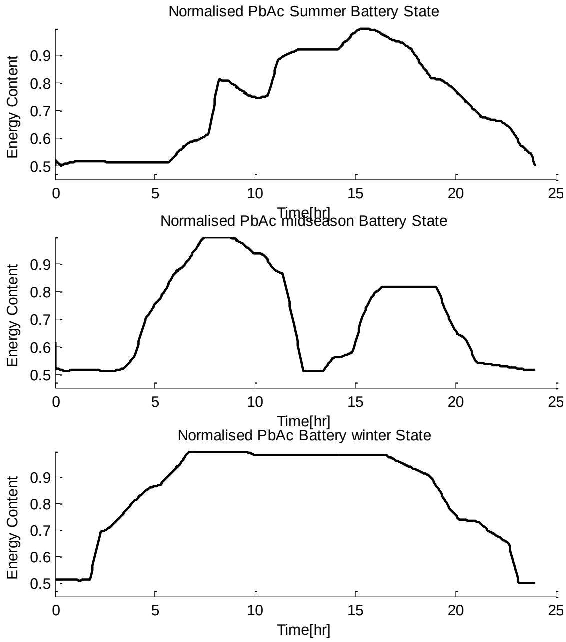

Figure 9 Normalised PbAc battery packs state. Normalised Li ion battery state of [top] summer [middle] midseason,[bottom]winter.

The amount of curtailed energy is assumed to be 20% of the PV generation in the neighbourhood. The net per annum cost of the case is 17,100 Euro/annum for Li ion and 12,100 Euro/annum for PbAc BESS. These values are net cost that should be injected to battery system to reach the breakeven.

7 ANALYSIS OF SIZING EFFECT ON DIFFERENT DESIGN PARAMETERS

The sizing variation depends on the amount of curtailed energy available in the distribution grid. The allowable limit of the transformer means the minimum limit from which BESS is subjected contribute to peak shaving of the transformer. In order to find the sensitivity on curtailed energy, 20% of total PV energy in summer is found to be enough for addressing the load and larger than that amount of PV energy in summer is assumed to be curtailed. Similarly, 45% of midseason PV energy is found to balance the load and more than of total PV energy is assumed curtailed energy. In winter no curtailed energy is expected. Here one preliminary assumption is the curtailed energy is free and flown to BESS without requirement of paying buying energy price. This increases the justification for using BESS along with PV system in smart distribution grid, can result in a cost-effective solution where the reduced electricity cost from having PV- battery coordination compensates the investment cost. If the amount of excess curtailed energy is large, then the optimum size is being increased. This can be visualized in Figure 10.

The apparent reason is that if the amount of excessive amount is high then the greater size of storage can contain free energy to sell it later to get more revenue. As the size increases the storage price also increases. But the excessive PV energy has a limit as well as the size of BESS that produces a limit on availability of free energy to be stored in BESS. Due to all these reasons the size of BESS has a weak positive correlation with available PV energy. Also in case of allowable transformer limit the size of BESS is also get decreased. To find the sensitivity on the buy and revenue on sizing a simple model of tariff is chosen. The buy and sell price of energy (per kWh) for BESS has a constant difference and the difference remains same on the whole year. It is apparent that the price difference has a positive correlation on sizing. An additional sizing sensitivity is done to find the sensitivity between allowable transformer loading and the size. The allowable transformer level is important as because this ensures the level of peak shaving application. The lower the allowable limit is, the higher the amount of energy needed for peak shaving. The optimum size get decreased in case of high level of allowable loading in transformer is permitted.

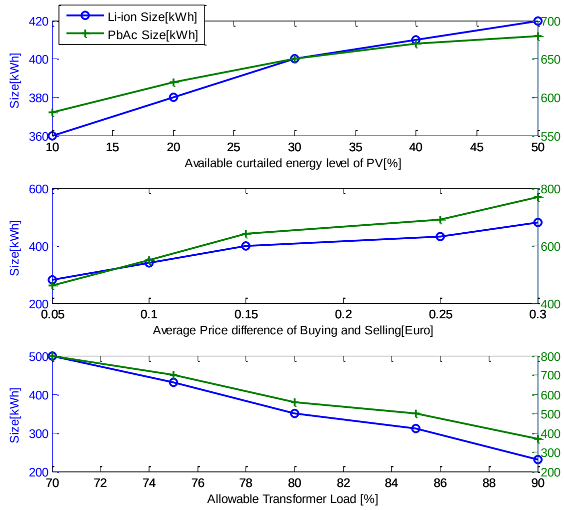

Figure 10: Sensitivity of different parameters on optimum sizing.

8 CONCLUSIONS

The extent of sizing of the storage to facilitate peak shaving in the electrical distribution grid is analysed while taken into account (deterministic) outdoor weather circumstances, heat demands, EV penetration, limitations of the LV-grid, and type, dimensions, limitations of the storage system. The peak reduction of 250 KVA transformers is achievable by applying an optimal control strategy on the deployed BESS. In this paper a mixed-integer linear programming (MILP) based optimal power flow model that satisfy the defined peak shaving of grid at the neighbourhood level with arbitrage participation has been proposed. Using the optimal flow result of different candidate BESS systems an optimal size can be found while minimising the yearly cost of energy. One of the findings of the paper is that BESS sizing depends on availability of curtailed energy that can be used to charge BESS (without payment of charging) in summer. The average price difference between buying and selling price of electricity for BESS and the allowable overloading limit of the transformer is also responsible for dimensioning storage for smart distribution grid. The comparison of two battery technologies is presented for the desired application. The current cost of BESS limits deployment opportunities to resolve site-specific issues. In terms of cost of energy, fluctuating electricity prices that may lead to attractiveness of charging a battery partly by grid electricity needs a good control mechanism as well as to gain the benefit the discharge mechanism must be conveyed with financially profitable motivation (a market concept is shown in the paper). The factors affecting method are availability of data, speed and accuracy of solution, and reliability goal of the energy system. The proposed method can utilise more commonly load profile variation and has an additional benefit of requiring relatively little computational and programming time while the mitigating the original problem of transformer congestion. The methodology offers flexibility in the overall design process as it takes account of all the feasible energy system configurations. The method can be adopted for other battery chemistries while incorporating alternate models or same model with different parameters for battery energy management calculation without loss of generality. The results presented are cost effective yet not always reliable energy system as using the method, the transformer will face some congestion in coldest winter days since optimum BESS size can supply energy limited by its availability and technical constraints. The influence of demand side management is not taken into account in this work. Although the developed method that considers adjusted load profile for storage sizing can be adopted for demand side management by altering the change of the load profile induced by demand side management using the same adjustment methodology. As the scheduling or demand side management algorithm has different facets of managing the loads and the end effect is the change of net load profile and using the same configuration it is foreseen that the proposed BESS sizing also can be obtained.

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